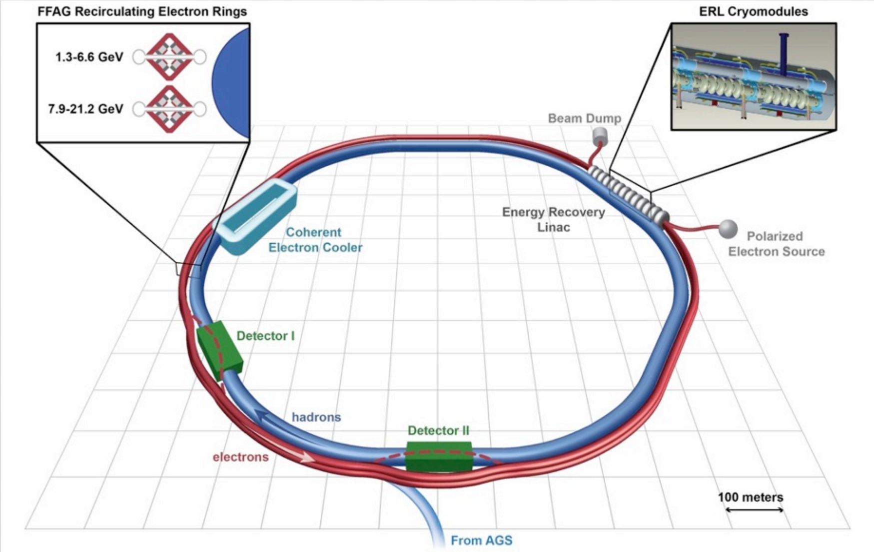
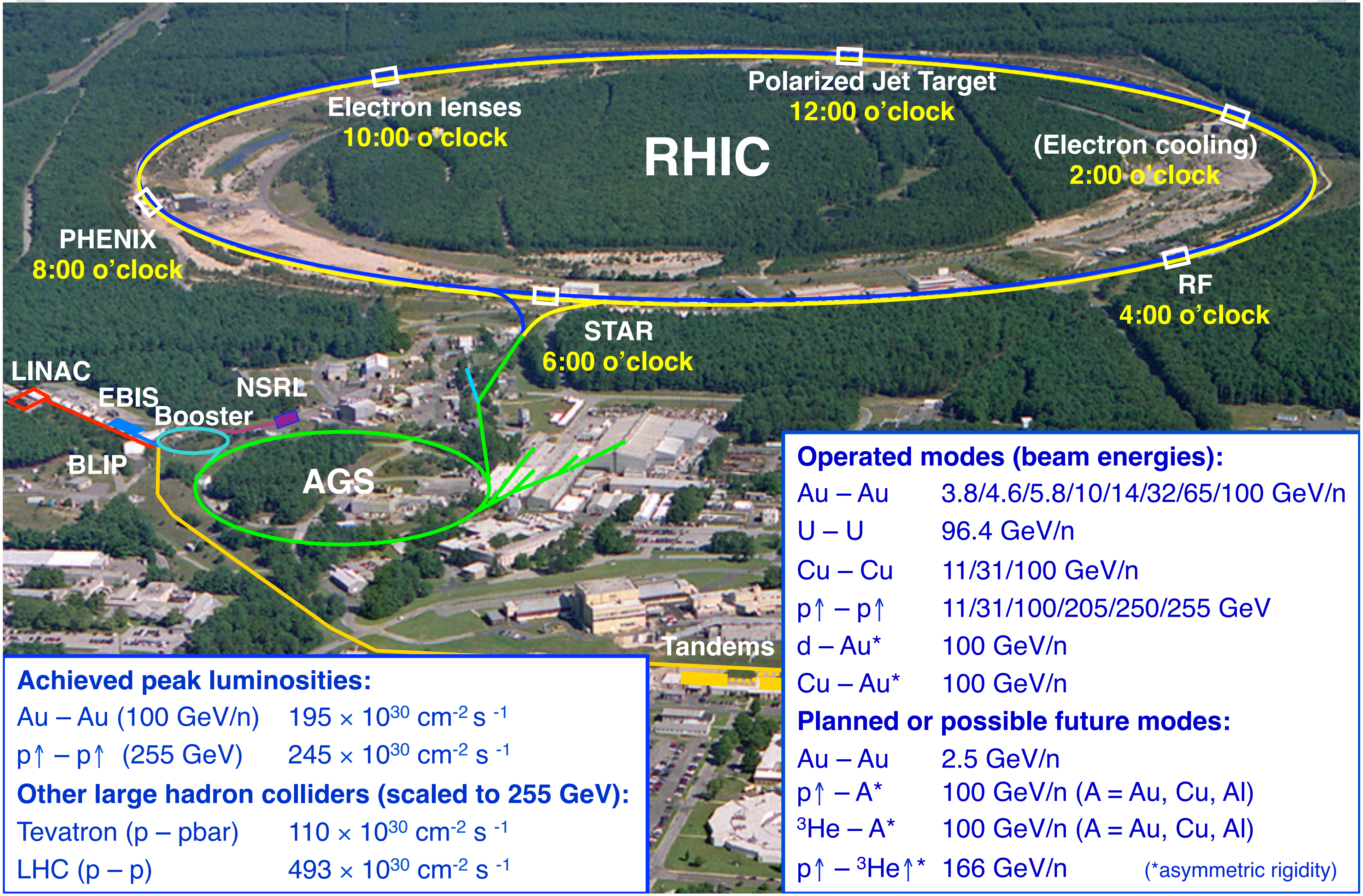


eRHIC Accelerator Design

V. Ptitsyn for the eRHIC design team

RHIC – a High Luminosity (Polarized) Hadron Collider



Achieved peak luminosities:

Au – Au (100 GeV/n)	195×10^{30} cm^{-2} s^{-1}
p↑ – p↑ (255 GeV)	245×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 255 GeV):

Tevatron (p – pbar)	110×10^{30} cm^{-2} s^{-1}
LHC (p – p)	493×10^{30} cm^{-2} s^{-1}

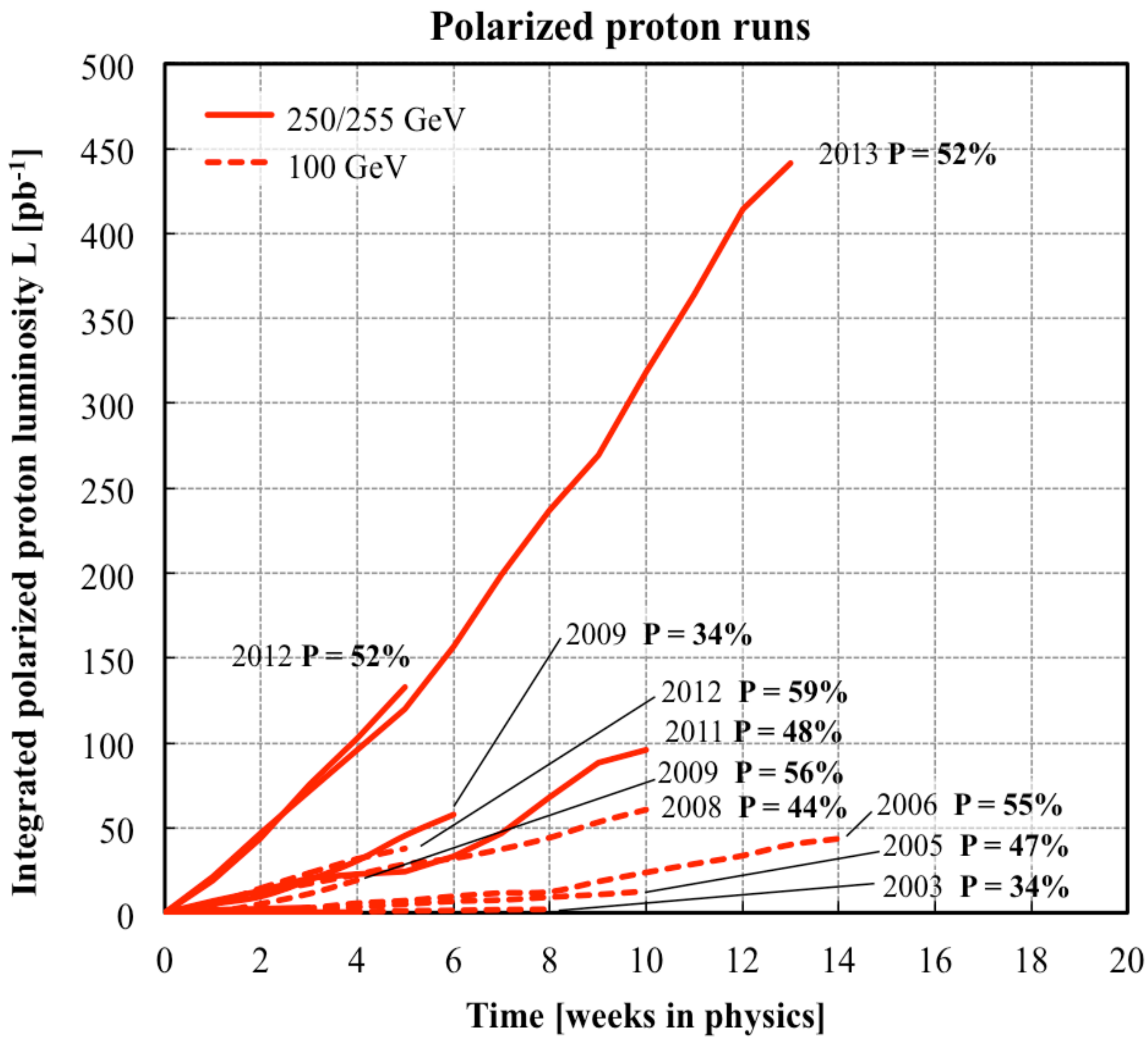
Operated modes (beam energies):

Au – Au	3.8/4.6/5.8/10/14/32/65/100 GeV/n
U – U	96.4 GeV/n
Cu – Cu	11/31/100 GeV/n
p↑ – p↑	11/31/100/205/250/255 GeV
d – Au*	100 GeV/n
Cu – Au*	100 GeV/n

Planned or possible future modes:

Au – Au	2.5 GeV/n
p↑ – A*	100 GeV/n (A = Au, Cu, Al)
^{3}He – A*	100 GeV/n (A = Au, Cu, Al)
p↑ – ^{3}He↑*	166 GeV/n

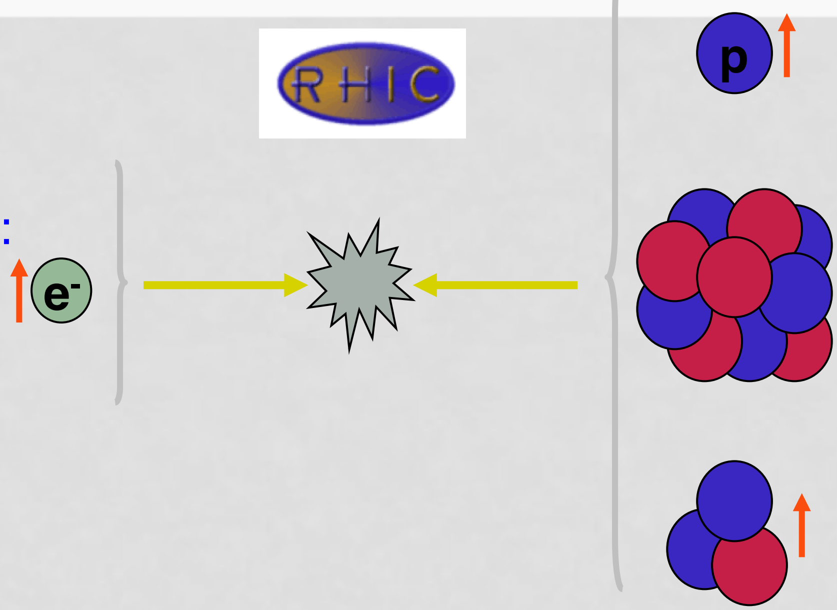
(*asymmetric rigidity)


Polarized proton runs
250/255 GeV
100 GeV
Integrated polarized proton luminosity L [pb^{-1}]
Time [weeks in physics]
2013 P = 52%
2012 P = 52%
2009 P = 34%
2012 P = 59%
2011 P = 48%
2009 P = 56%
2008 P = 44%
2006 P = 55%
2005 P = 47%
2003 P = 34%
0
50
100
150
200
250
300
350
400
450
500
0
2
4
6
8
10
12
14
16
18
20

eRHIC: QCD Facility at BNL

Add an electron accelerator to the existing $2.5B RHIC
including existing RHIC tunnel and cryo facility

80% polarized electrons:
6.6 – 21.2 GeV

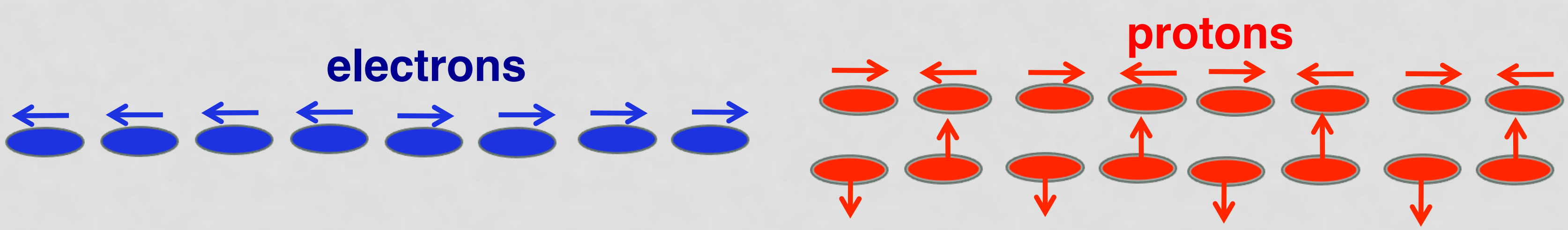


70% polarized protons
25 - 250 (275*) GeV

Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 - 100 (110*) GeV/u

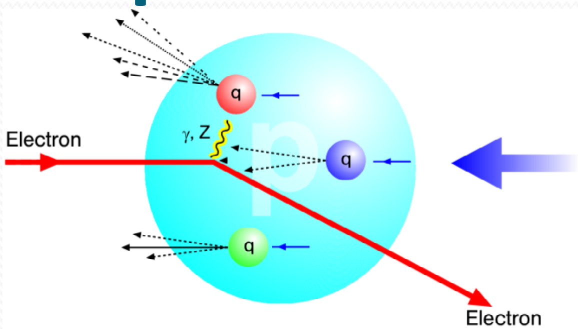
Pol. light ions (He-3)
17 - 167 (184*) GeV/u

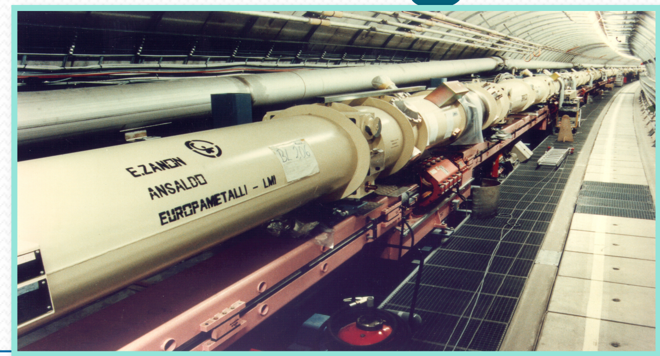
Center-of-mass energy range: 30 – 145 GeV
Any polarization direction in electron-hadron collisions



*** It is possible to increase RHIC ring energy by 10%**

Lepton-nucleon scattering





- **Deep Inelastic Scattering (DIS)** of electron, muon and neutrino beams on nucleons (fixed targets) has been a vital scientific exploration tool for several decades.
- Experiments at SLAC (late 60s) led to the quark-parton model of nucleons, and ultimately to establishing QCD theory.
- Numerous DIS experiments in 70-80s uncovered the momentum and spin distribution of quark constituents of proton and neutron

HERA (1991-2007): first electron-proton collider

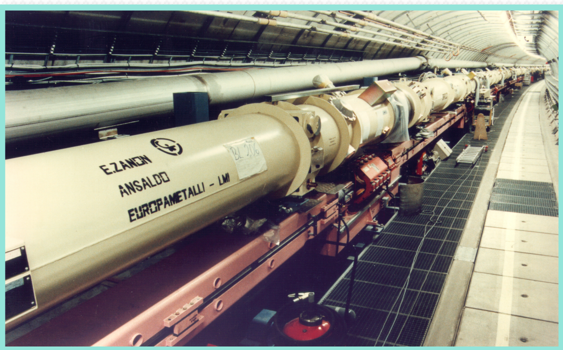
Higher CME -> reach to the momentum distribution of quark and gluons at very low momentum fraction (x)

Selection of physics results:

- **precise data on details of the proton structure**
- **the discovery of very high density of sea quarks and gluons present in the proton at low-x**
- **detailed data on electro-weak electron-quark interactions**
- **precision tests of QCD (α_s measurements)**

From HERA to future EICs

HERA

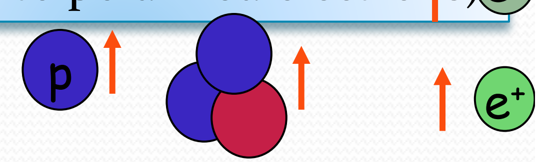


Polarized e^-,e^+ (27.5 GeV)
Unpolarized protons (920 GeV)
Peak luminosity: $5 \cdot 10^{31}$ cm^{-2} s^{-1}

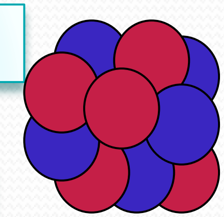
Future colliders

Much higher luminosity:
10^{33}-10^{34} cm^{-2} s^{-1}

Polarized protons and light ions
(in addition to polarized electrons) e^-

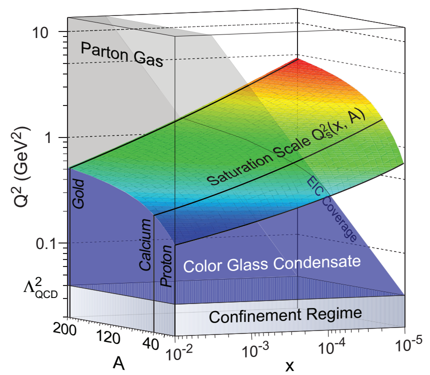


Heavy ion beams



Different (and variable)
Center-of-Mass Energy
range

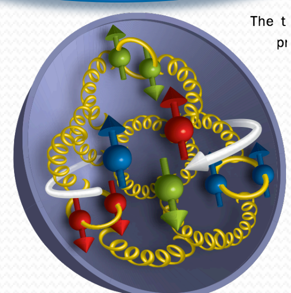
Major physics objectives of eRHIC

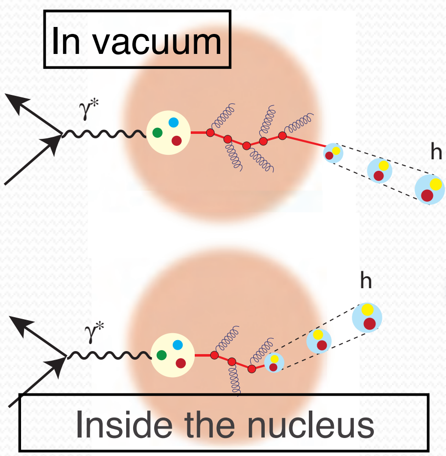


Mapping the gluon content of ions and protons;
High-density gluon state

3-dimensional imaging of the nucleons

eRHIC

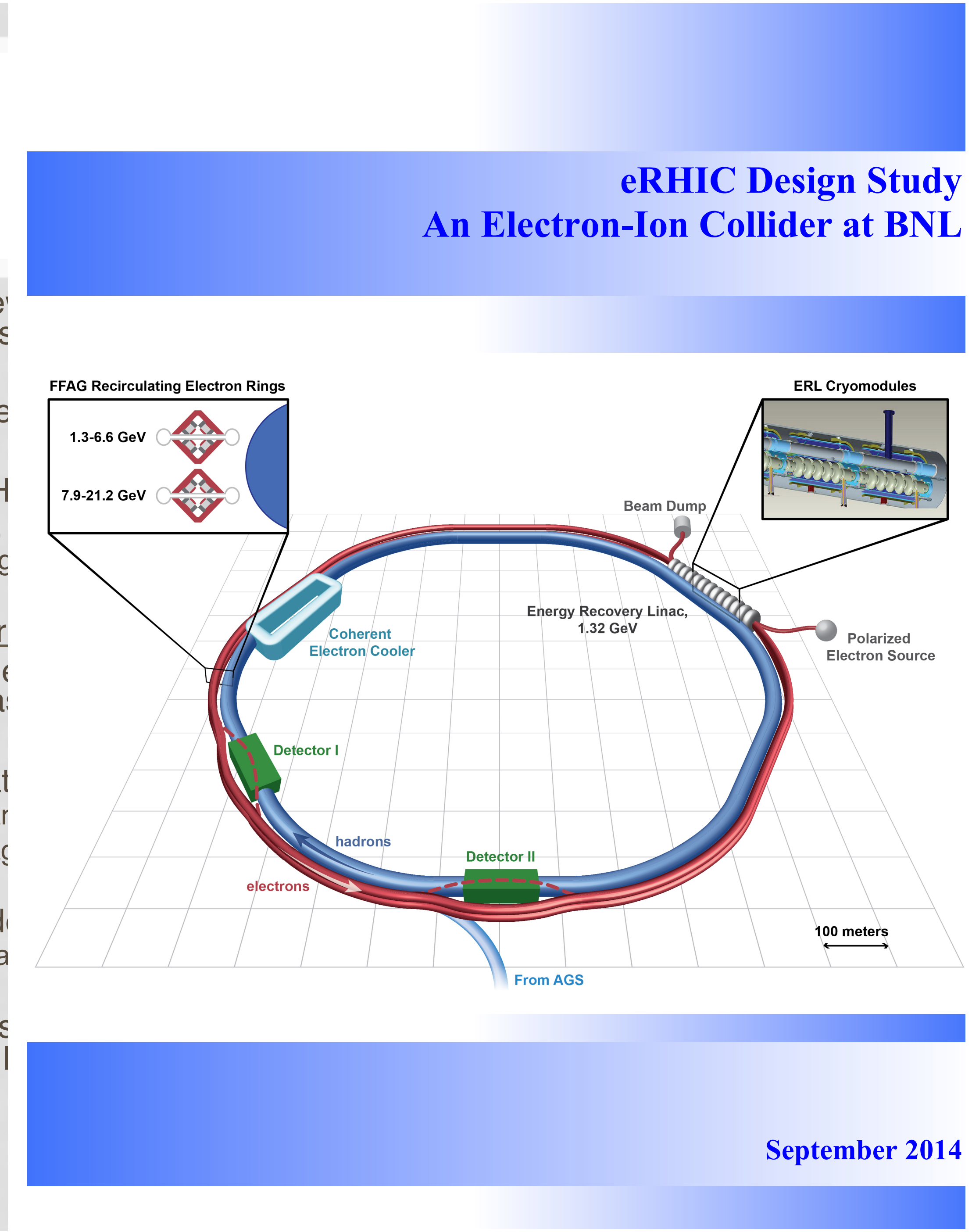




Parton distributions and interaction in nuclei

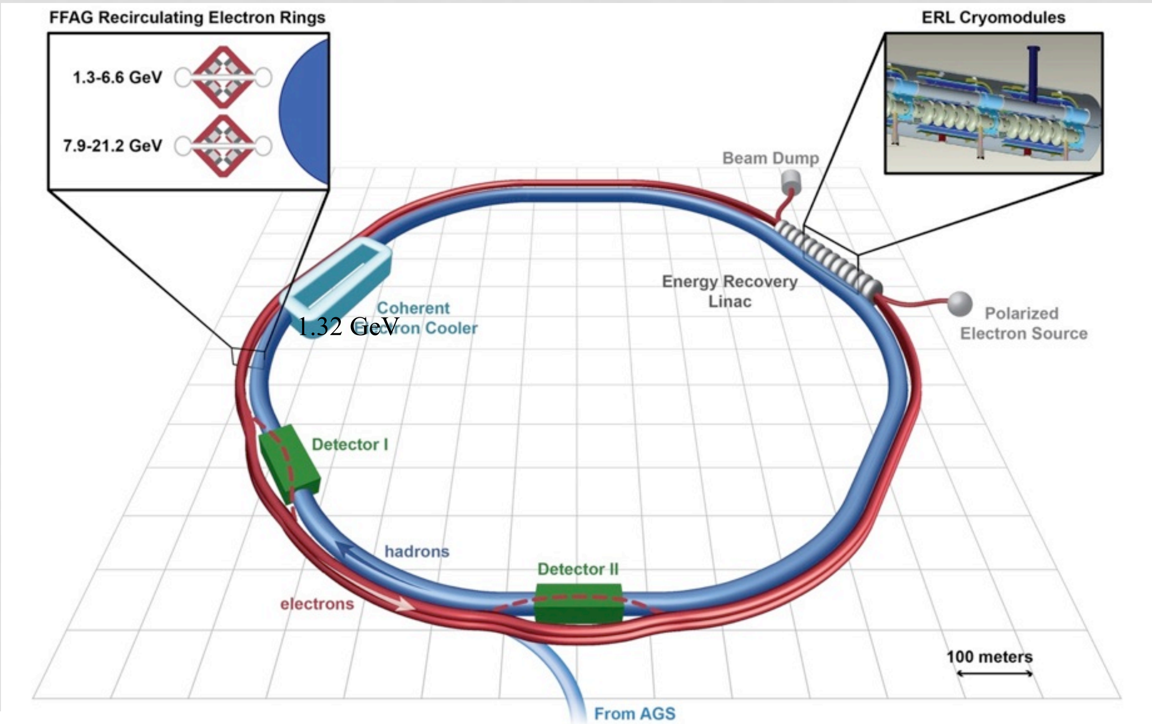
Probing the nucleon's spin structure

- I. Ben-Zvi, J. Ke ... Nuclear Instrumentations
- eRHIC ZDR (the ... 004).
- ERL-based eRH ... ation
  - $L\sim10^{34}\ cm^{-2}\ s^{-}$,
  - Energy staging
- 2012-2013: Wor
- Bottom-up cost e ... ith separated re-circulating pa
- FFAG re-circulat
  - construction ar
  - No energy stag
- 10 GeV FFAG d ... 13) :
  "The MAC congratula ... t."
- The "eRHIC Des ... ng main features of eRHI



FFAG eRHIC Design

- Up to 21.2 GeV electron beam accelerated with Energy Recovery Linac (ERL) inside existing RHIC tunnel collides with existing 250 GeV polarized protons and 100 GeV/n HI RHIC beams
- Single collision of each electron bunch allows for large disruption, giving high luminosity and full electron polarization transparency
- Use 2 FFAG magnet strings in RHIC tunnel to transport up to 16 beams
- Considered permanent magnet design for FFAG lattice magnets
- Cool hadron beam 10-fold in all directions using coherent electron cooling (CeC) at reduced intensity of hadron beam
- IR design with β*= 5 cm using SC magnet technology and crab-crossing scheme
- Average polarized electron current of 50 mA



eRHIC beam parameters and luminosities

	e	p	$^{3}He^{2+}$	$^{197}Au^{79+}$
Energy, GeV	15.9	250	167	100
CM energy, GeV		122.5	81.7	63.2
Bunch frequency, MHz	9.4	9.4	9.4	9.4
Bunch intensity (nucleons), 10^{11}	0.33	0.3	0.6	0.6
Bunch charge, nC	5.3	4.8	6.4	3.9
Peak luminosity, 10^{33} cm^{-2}s^{-1}		1.5	2.8	1.7

Future luminosity upgrade

The proton beam intensity is only at ~15% of present level.

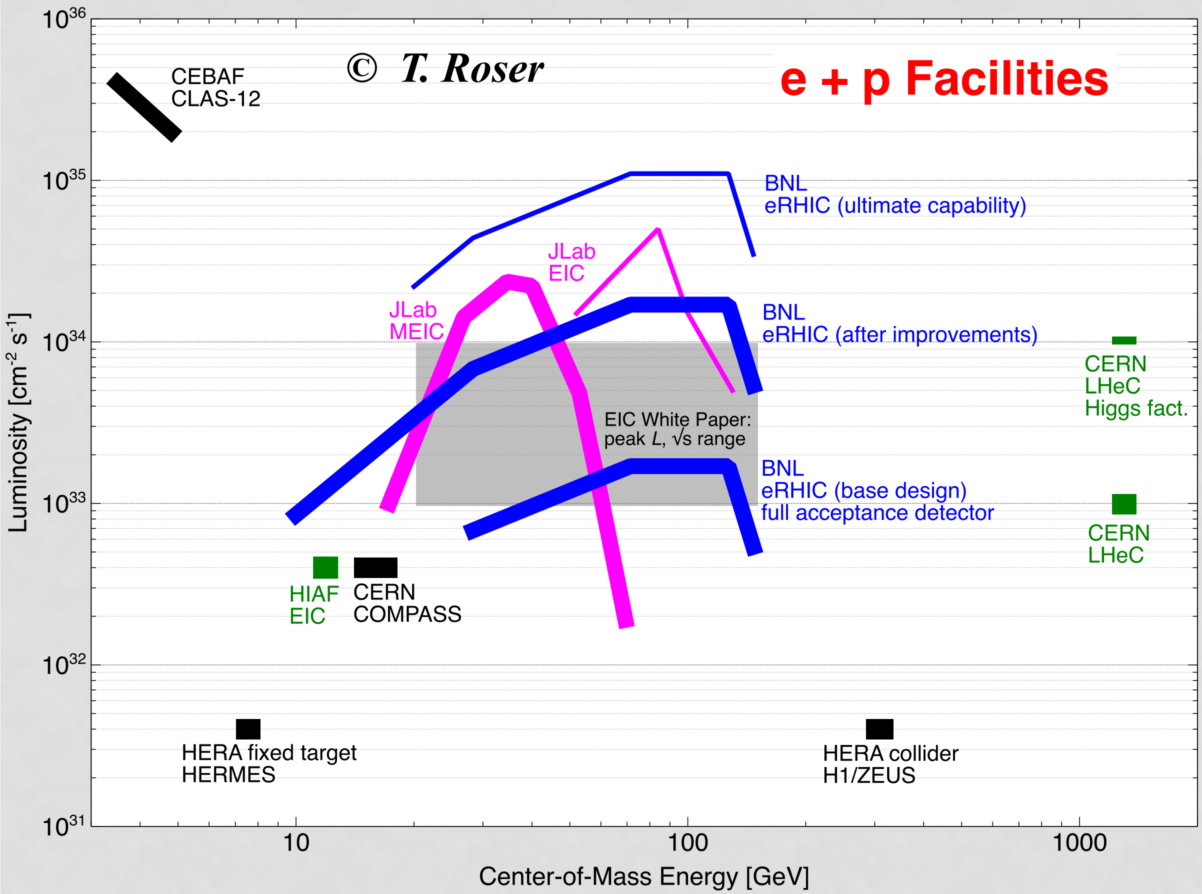
Open path to the moderate cost luminosity upgrade the future by increasing the hadron beam intensity (by an order of magnitude) and related hadron ring improvements:

copper coating of beam pipe, beam diagnostics upgrade, RF system upgrade

Luminosity above 10^{34} cm^{-2} s^{-1} can be reached

$$L = f_c \xi_h \frac{\gamma_h}{\beta_h^*} \frac{ZN_h}{r_h} H_{hg} H_p$$

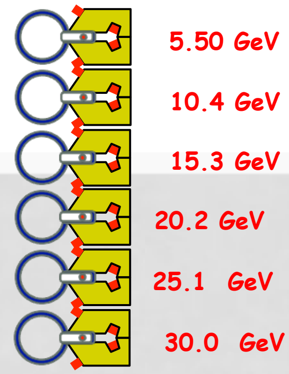
Luminosity vs CEM



Factors defining eRHIC luminosity:

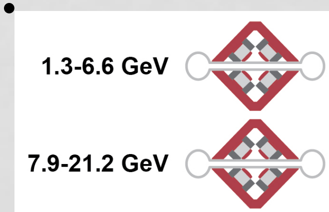
- Electron source current
- Electron synchrotron radiation
- Hadron beam-beam limit
- Hadron space charge limit
- Detector energy asymmetry requirements

Why FFAG eRHIC?



Until 2013 the high luminosity ERL-based eRHIC has been designed with individual recirculation passes.

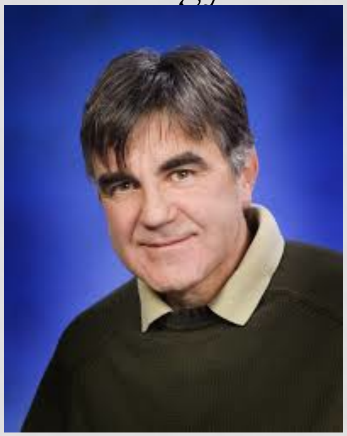
Main arguments for using FFAG for beam recirculation:



Construction cost saving: 2 FFAG beam lines instead of numerous separate recirculation passes .
Other view: Possibility to reach higher electron beam energy at the same cost.

Operation cost saving: potential of using permanent magnet technology for FFAG beam lines.

Dejan Trbojevic
Campaining for NS-FFAG eRHIC approach for many years.



Demonstrating feasibility of NS-FFAG lattice design approach

- Optimization of FFAG cell design to minimize synchrotron radiation, orbit spread, path length spread, …

- Development of the lattice solutions for detector bypasses, straight sections, arc-to-straight matching sections, a technique for extraction into the IR beamline from the FFAG beamline.

- Beam orbit measurements and corrections in the FFAG beam lines

Theoretical analysis methods and simulation tools have been developed to resolve the listed tasks.

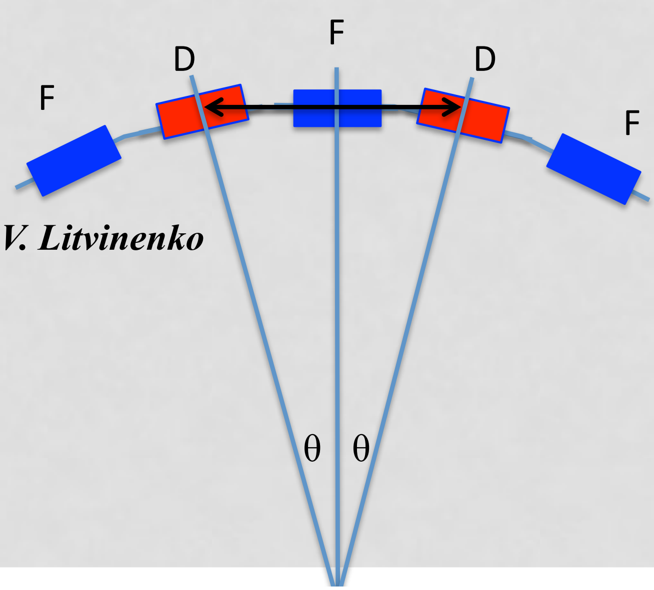
NS-FFAG approach for eRHIC

- Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) approach is used for eRHIC recirculation passes. It can transport large energy range.
- eRHIC FFAG cell is comprised of two quadrupoles (F & D) whose magnetic axes are shifted horizontally with respect to each other by an offset Δ.

  It can be considered as *strongly focusing, bent FODO cell*

  Small quadrupole offsets bend the beams adiabatically if bend radius is much larger than cell length
- Orbit and optics dependence on the energy can be accurately found in paraxial approximation

$L=2(l_F+l_D+2d)$



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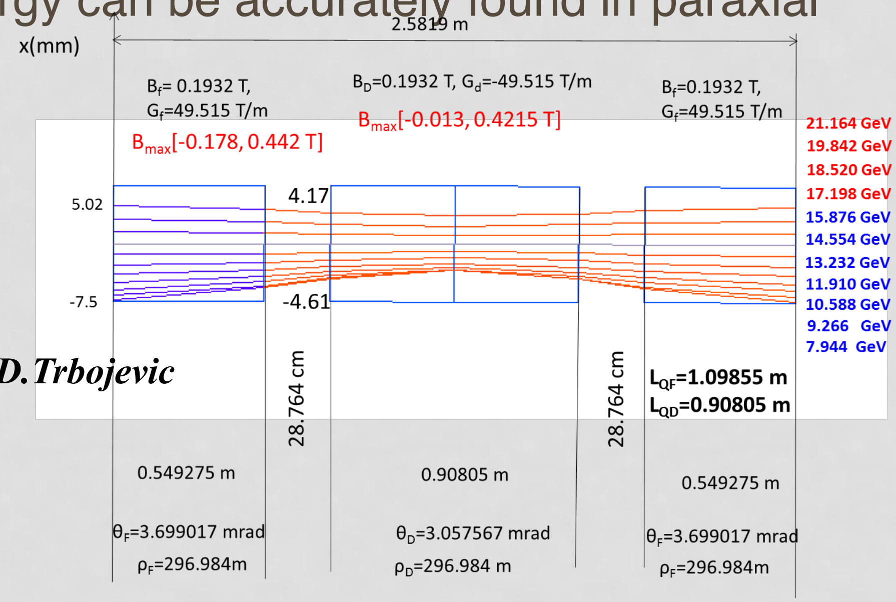

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High energy FFAG cell

FFAG Recirculation Passes

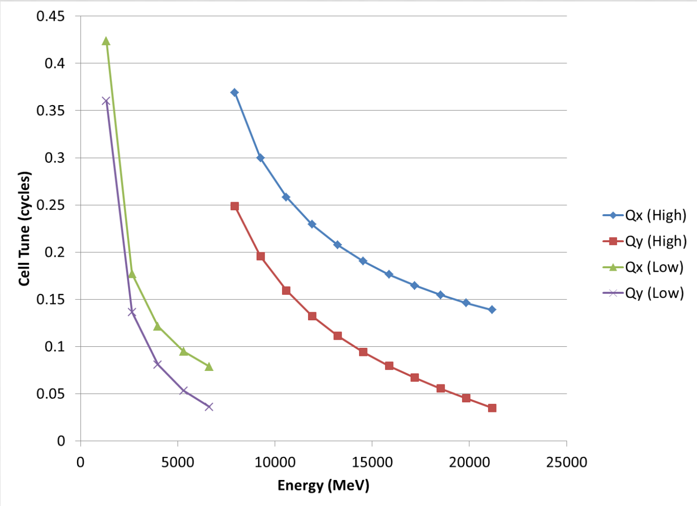
FFAG lattice was thoroughly optimized on several factors:

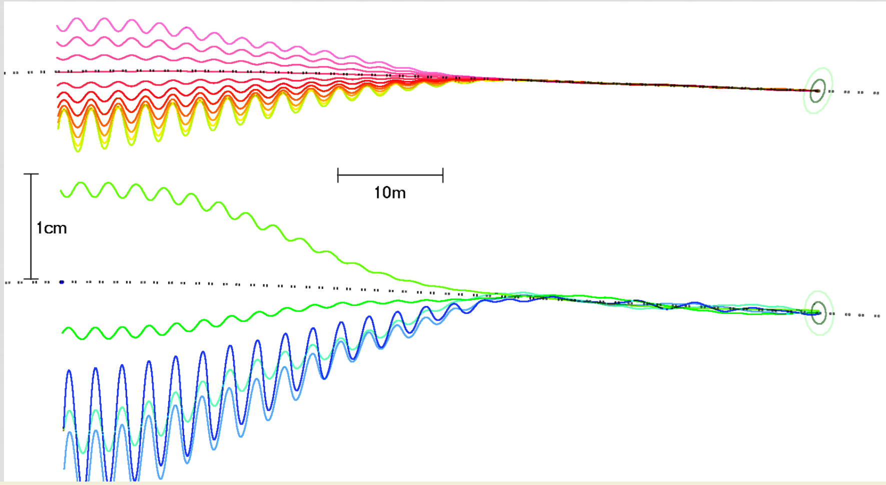
- energy acceptance
- orbit spread
- time-of-flight spread
- synchrotron radiation power

Cell parameters for both FFAGs

Element	Length (m)	Angle (mrad)	Gradient (T/m)	Offset (mm)
All Drifts	0.288	0		
BD (Low)	0.908	3.058	9.986	-6.947
QF (Low)	1.099	3.699	-9.006	6.947
BD (High)	0.908	3.058	49.515	-3.901
QF (High)	1.099	3.699	-49.515	3.901

© D.Trbojevic, S. Brooks

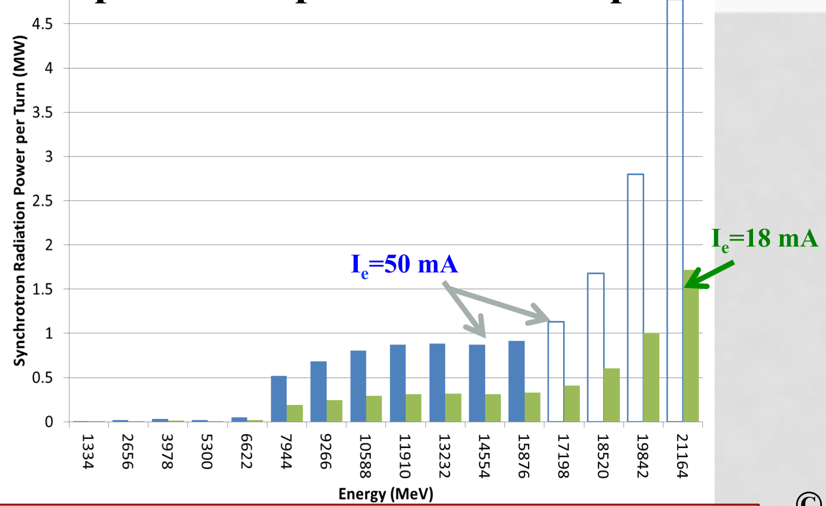




Transition from arc section to straight section is done by gradual reduction of quadrupole offsets

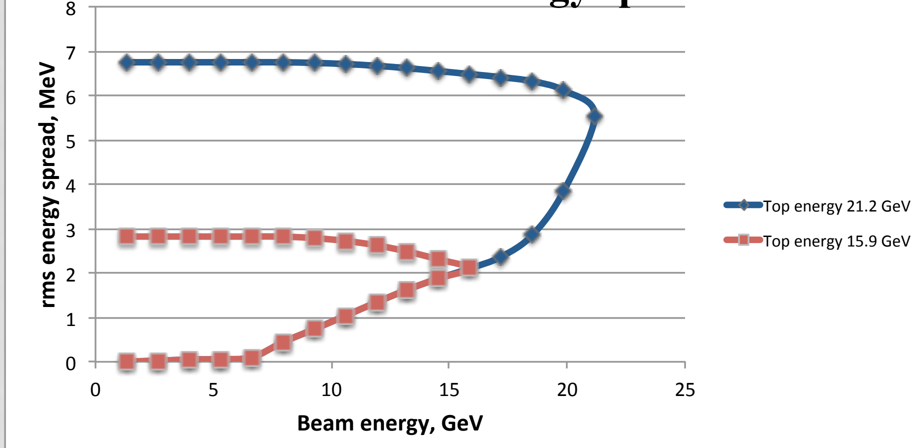
Synchrotron Radiation Effects

SR power loss per recirculation pass



Total SR power 12 MW:
operation at 15.9 GeV top energy -> 50 mA
operation at 21.2 GeV top energy -> 18 mA

Accumulated energy spread



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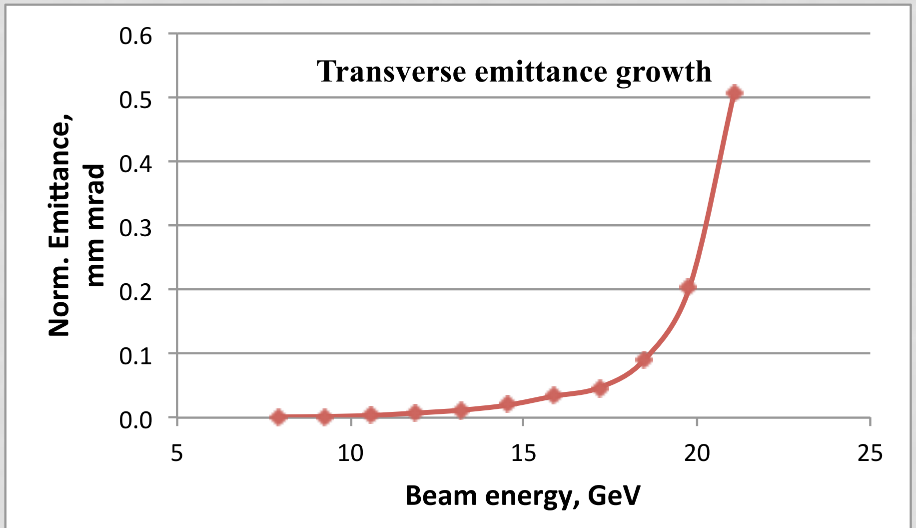


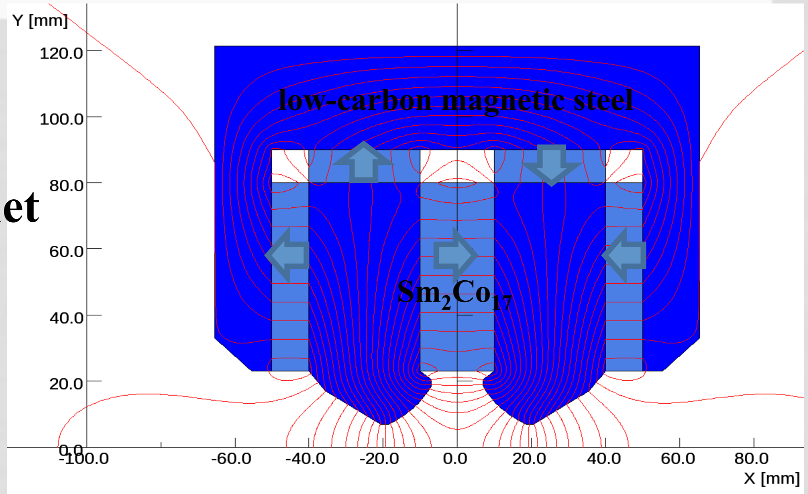
Energy loss compensation schemes :

- 2^{nd} harmonic (844 MHz) cavities; or
- main linac RF phase offset + high harmonic cavities

Permanent Magnet Design

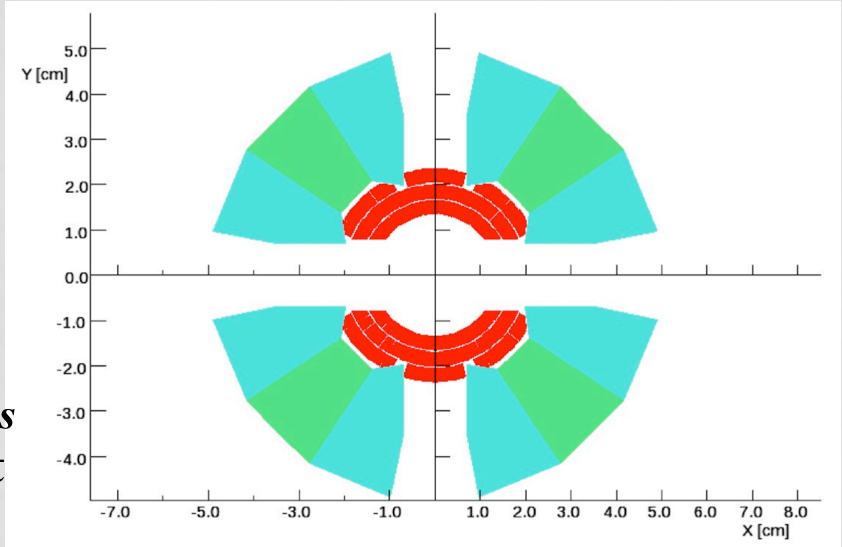
- FFAG lattice can be realized with permanent magnets
- Expected construction and operational cost savings
- Expected field quality < 10^{-2}
- SmCo: acceptable B_r, good temperature stability, exceptional radation resistance

© W. Meng
Hybrid magnet

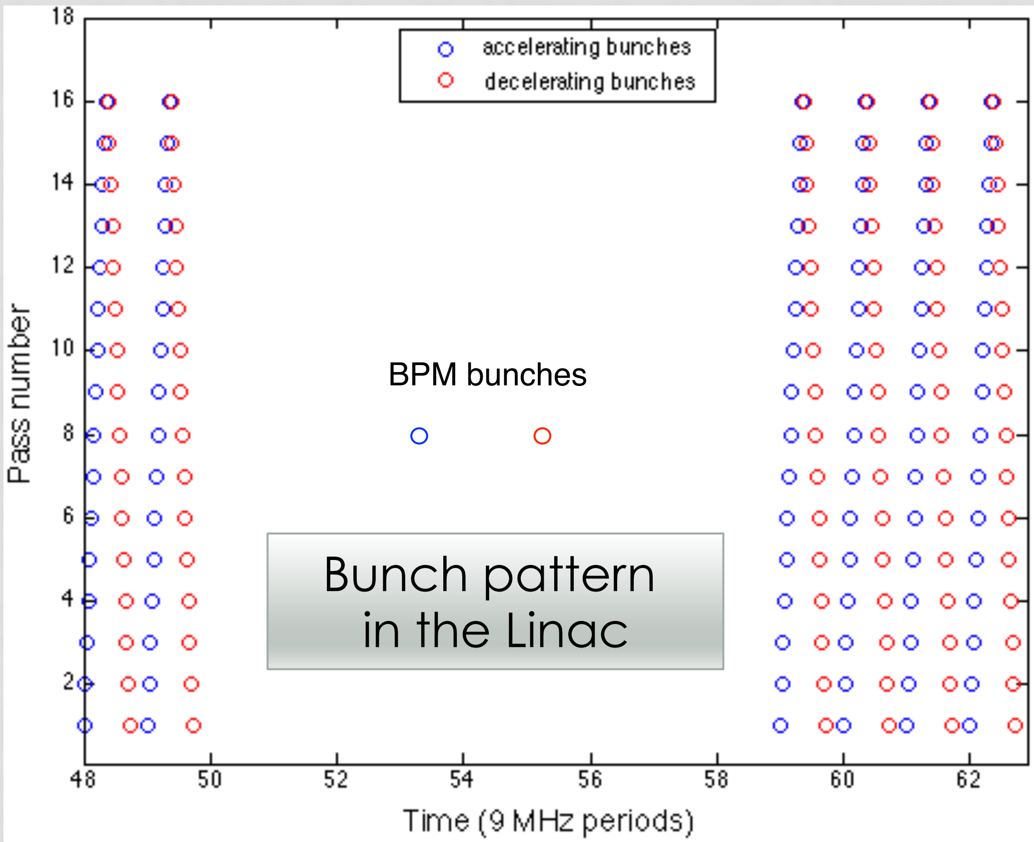


Different designs of 50 T/m permanent magnet have been under consideration. Including 1% dipole and quadrupole correction coils.

© N. Tsoupas
Halbach magnet



e-Beam Bunch Pattern



- The bunch pattern is defined by the length of electron circumference.
- Presently one RF bucket shift between the bunches. Half-bucket shift at the top energy pass.
- ~ 900 ns gap to eliminate ion accumulation
- For orbit measurements of individual passes: bunches in the gap are introduced. *Every 16 RHIC revolution periods inject one bunch into the gap.*

Beam Spreader and Combiner

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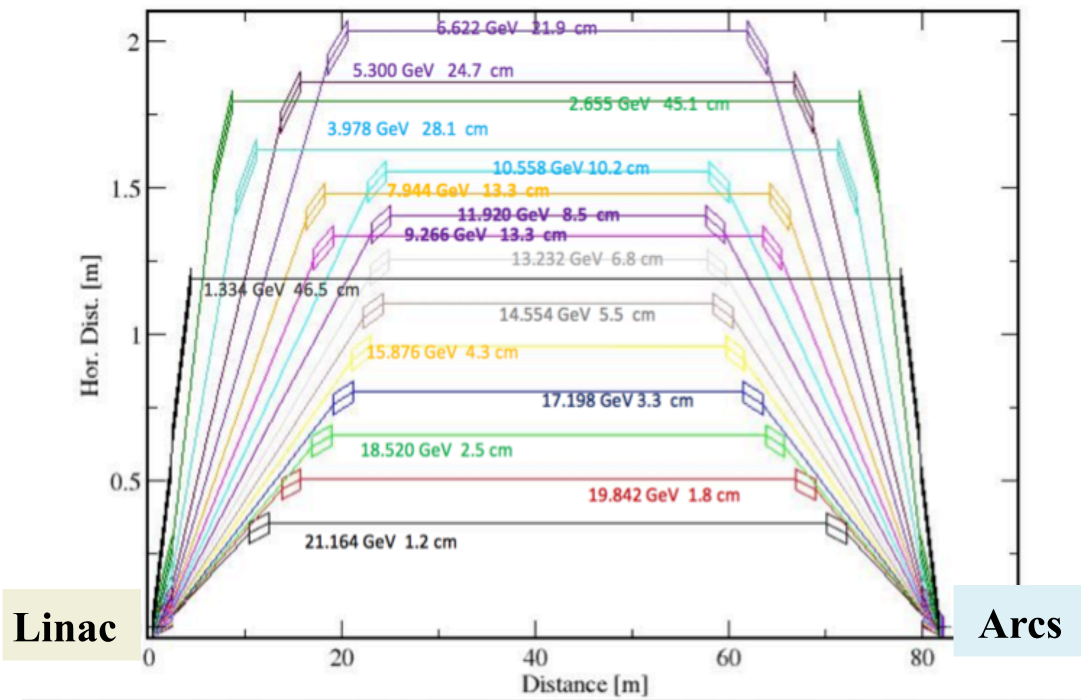
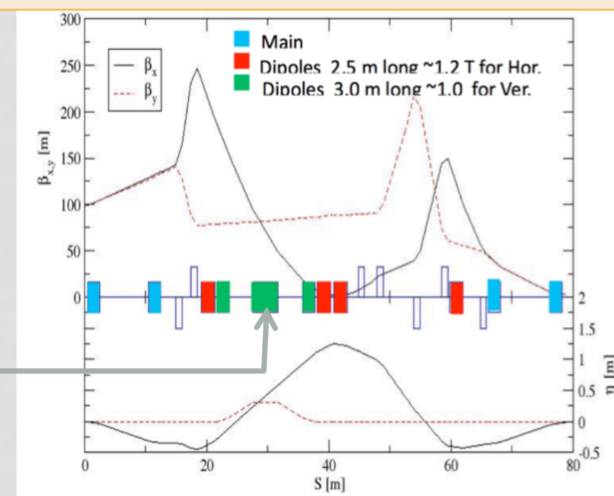


- Placed on either side of the linac to separate/combine the 16 beams with different energies between FFAG arcs and CW Linac
- Match optical function from the arc to the linac
- Ensure isochronous one turn transport:

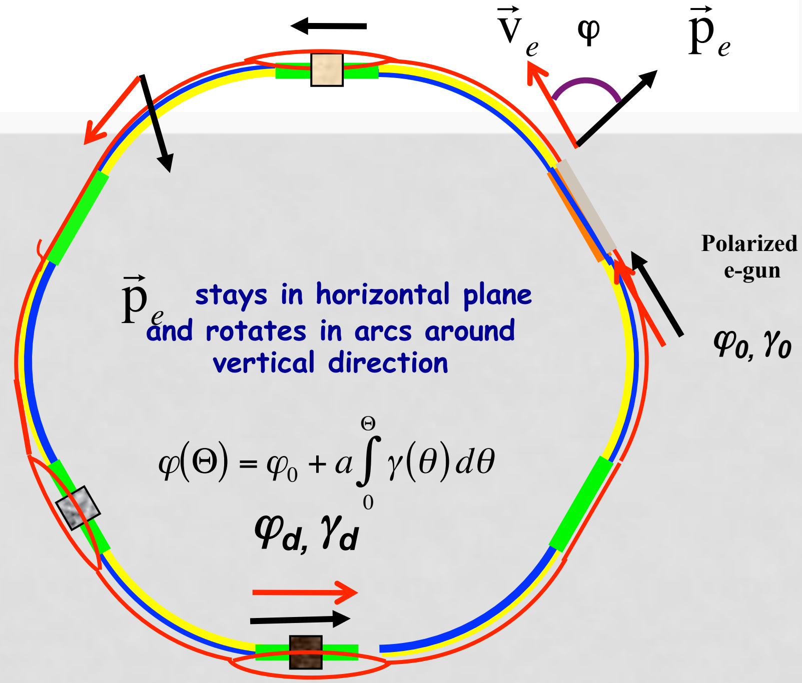
  path length and R_{56} corrections
- Betatron phase advance adjusters

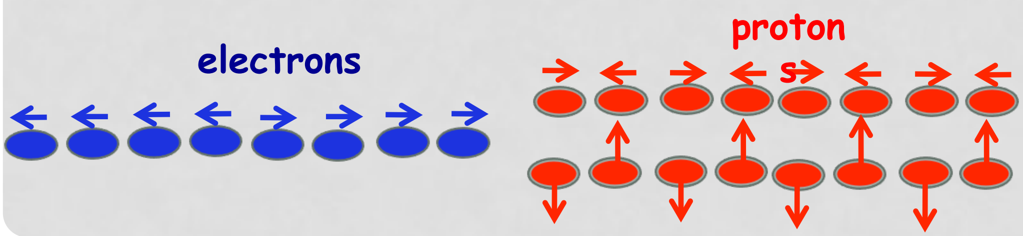


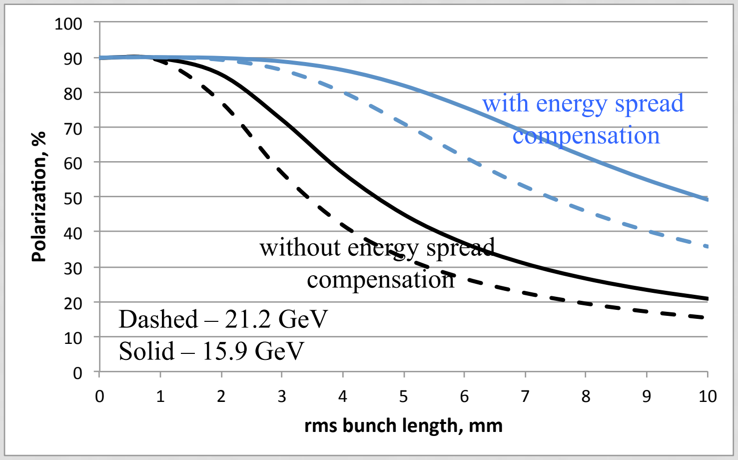
- ✧ **15 cm horizontal separation between individual lines**
- ✧ **Some of the lines are folded into the vertical plane to reduce path length difference**
- ✧ **Vertical magnet chicanes are used for pathlength correction**

Electron Polarization in eRHIC

- 90% longitudinally polarized e-beam from DC gun with super-lattice GaAs-photocathode with polarization sign reversal by changing helicity of laser photons.
- Only longitudinal polarization is needed in the IPs.
- eRHIC avoids lengthy spin rotator insertions. Cost saving.
- Integer number of 180-degrees spin rotations between the gun and IPs
- With the linac energy of 1.322 GeV the polarization is longitudinal at both experimental IPs
- To achieve 80% polarization up to 21.2 GeV harmonic cavities are used for the energy spread reduction







Hadron-Electron Synchronization

Main synchronization condition:
the electron and hadron bunch repetition frequencies at the collision points have to be the same:

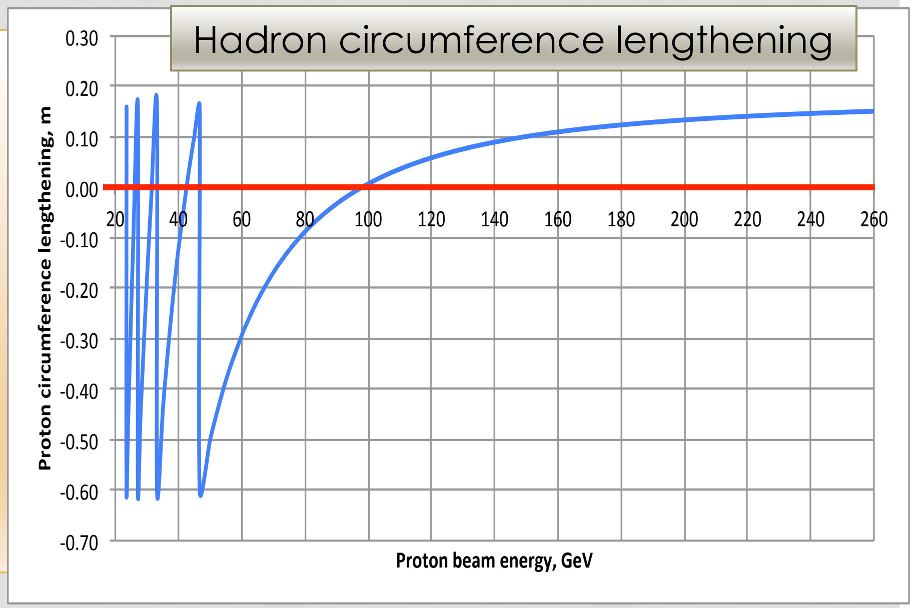
$$f_{be} = f_{bh}$$

The hadron bunch frequency (at the fixed circumference) depends on the hadron energy

Presently solution:

- **Hadron delay**
  Radial orbit offset in hadron ring:
  Up to 16 cm path lengthening ability.

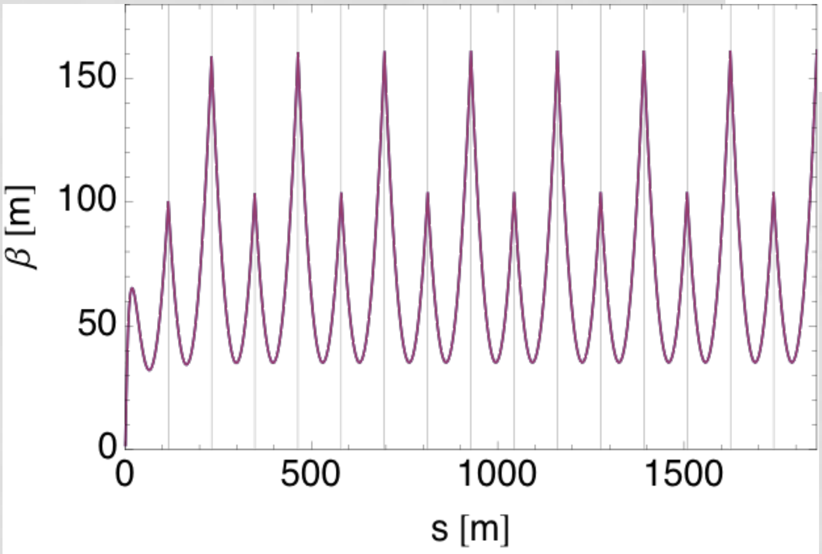
- **The RF harmonic switching method;**
  Used to operate with the hadron energies <50 GeV/n



SRF Linac

Energy Recovery Linac:

- 422 MHz SRF cavities
- 120 m cold length
- no quadrupoles



The beta function in the linac for 16 passes.
The horizontal and vertical optics are identical.
The grid lines separates the optics of each pass.

© ***Y. Hao***

Multipass beam-breakup thresholds for 16 pass operation (simulation results)

Δf/f (rms)	Current Threshold (mA)
0	53
5e-4	95
1e-3	137
3e-2	225
1e-2	329

HOM frequency spread

Additional SRF systems:

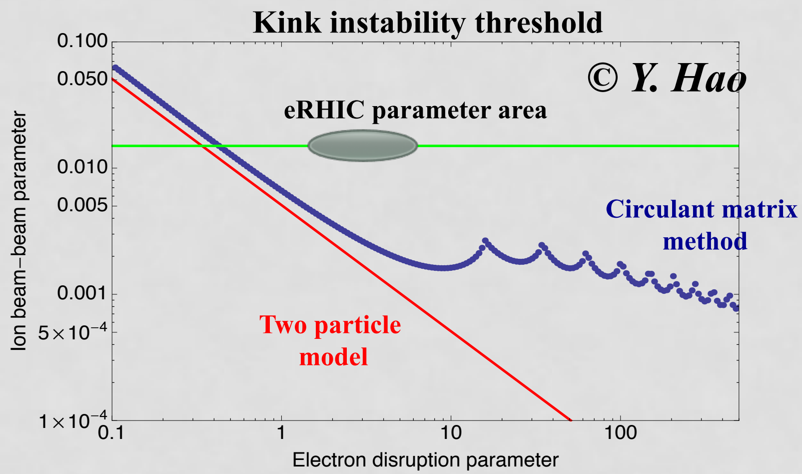
- Energy loss compensation (2^{nd} harmonic)
- Energy spread reduction (3^{rd} or 5^{th} harmonic)

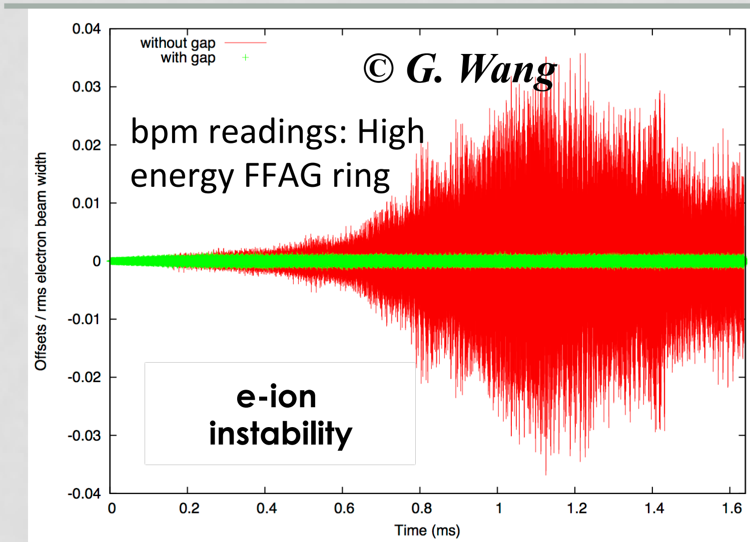
Beam Dynamics

- Beam-beam
- e-beam disruption (*emittance increase by ~30%*)
- Luminosity enhancement by e-beam pinching: *33%*
- Kink instability of hadron beam:

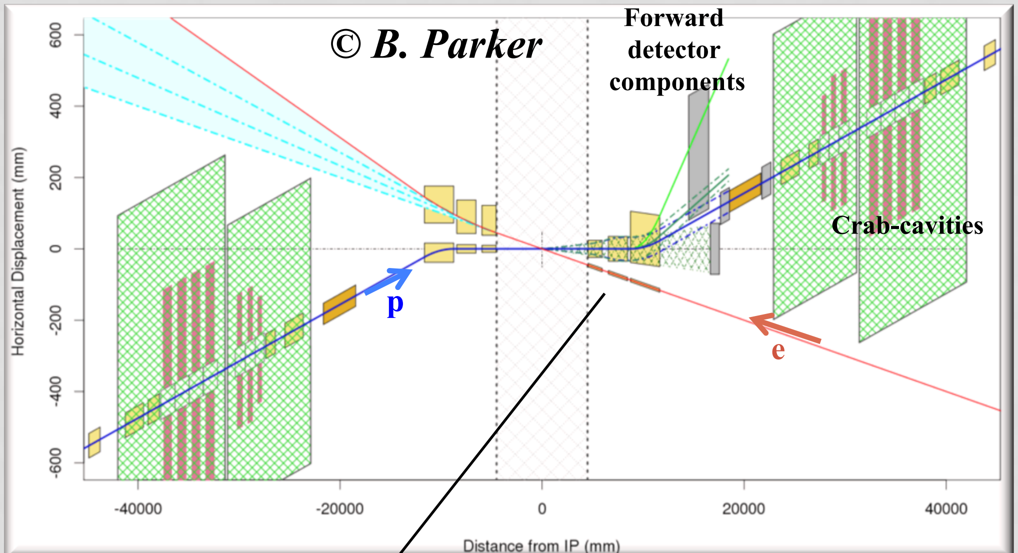
  the feedback system (50-300 MHz) damps the instability
- Hadron beam heating by electron parameter noise
- Multi-pass BBU
- Single bunch BBU
- Electron-ion interactions
  - Gap is introduced to prevent ion accumulation
  - Fast ion instability simulations
- Energy spread due to impedances: ~18 MeV

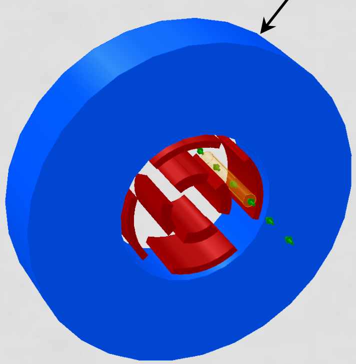
  Compensation schemes are under studies





Interaction Region with β^* = 5 cm





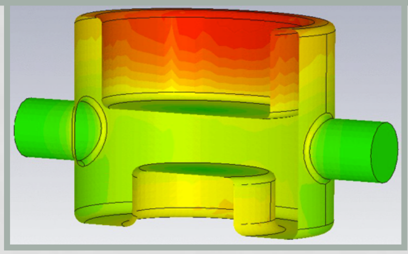
Electron passage is arranged between SC coils of hadron magnet

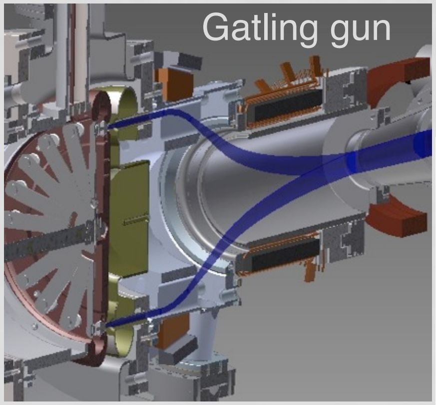
- 10 mrad crossing angle with crab-crossing
- Large enough aperture IR SC magnets for forward collision products and with field-free passage for electron beam
- Recent IR design improvements on the magnet design with electron passage and integration of detector components
- 90 degree lattice and beta-beat in adjacent arcs (ATS) to reach β^* of 5 cm and provide effective chromatic corrections

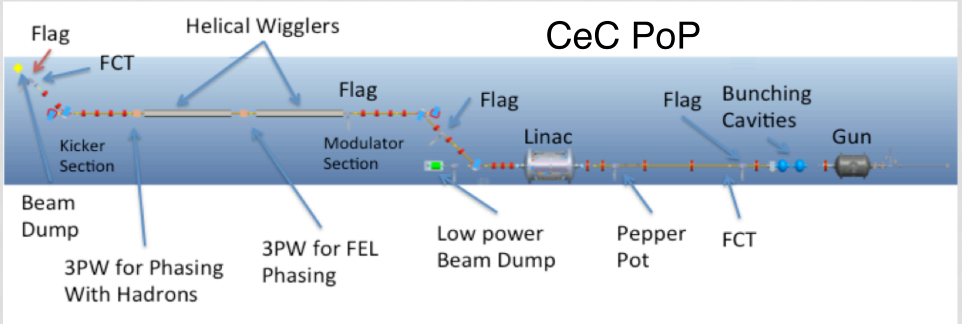
eRHIC R&D

- Prototyping of Gatling Gun polarized electron source
- Coherent electron Cooling PoP using 40 GeV/n Au beams in RHIC
- High average current ERL to support operation with high current e-beam
- Prototype eRHIC ERL with FFAG arcs (@ Cornell ?)
- Development of high gradient crab cavities within LARP
- Development of polarized He-3 (underway in collaboration with MIT)

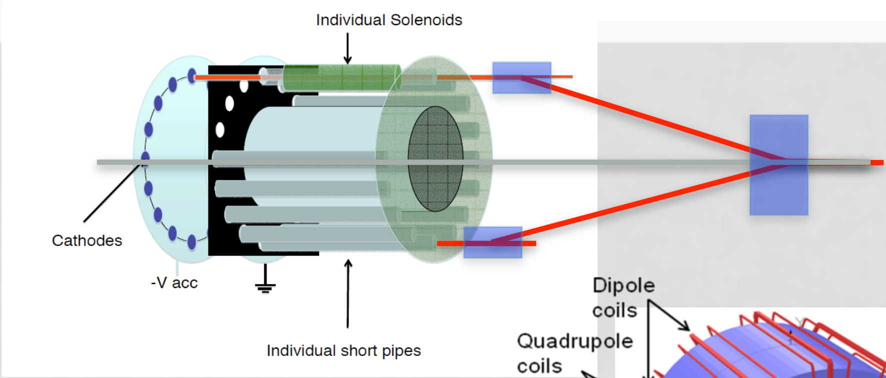
QWR crab-cavity design (BNL)

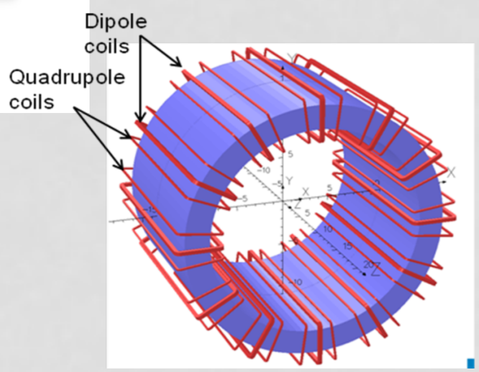




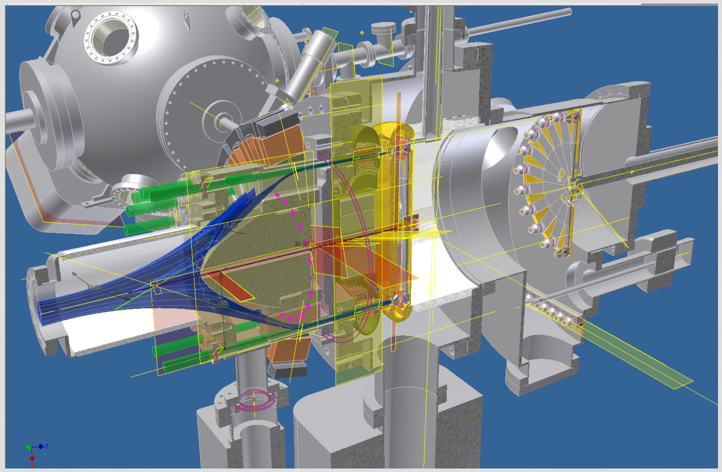


50 mA polarized electron source R&D





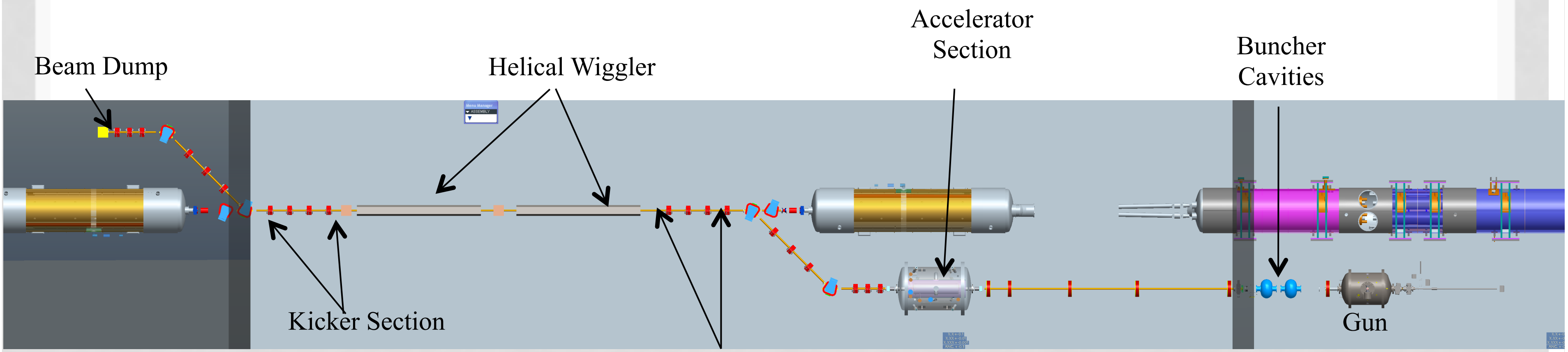
BNL Gatling Gun:
the current from multiple cathodes is merged



I. Ben-Zvi
V. Litvinenko
J. Skaritka

- Prototype with 20 potential cathodes has been built
- Photo current from two cathodes during first test at Stangenes Industries (CA)
- End of 2014: test with two cathodes in Stony Brook

Proof-of-principle CeC Experiment in RHIC IP2



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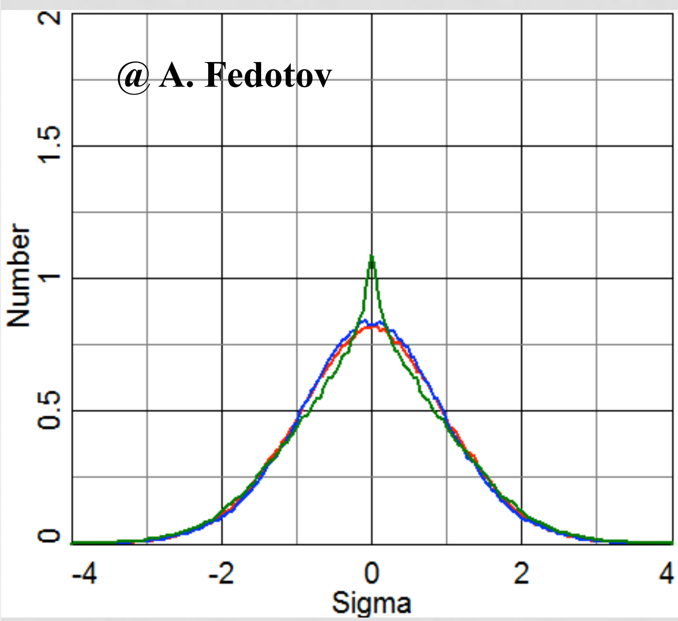


Coherent Electron Cooling:

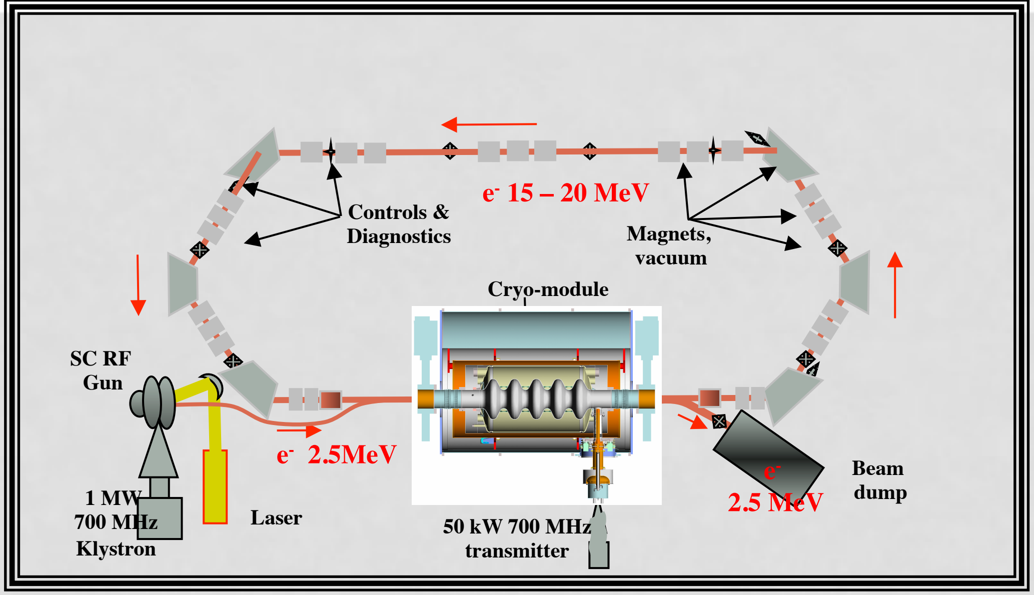
- Idea proposed by Y. Derbenev in 1980, novel scheme with full evaluation developed by V. Litvinenko.
- Fast cooling of high energy hadron beams is necessary for eRHIC luminosity
- Made possible by high brightness electron beams and FEL technology

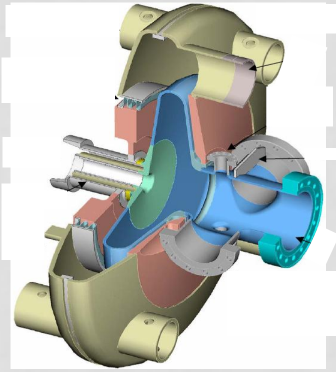
Proof-of-principle demonstration planned with 40 GeV/n Au beam in RHIC (2016)

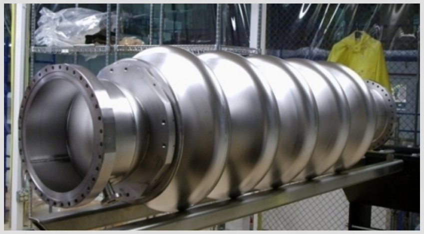
Aim : to demonstrate longitudinal cooling of 40 GeV/u Au ion bunch in RHIC

Energy Recovery Linac Test Facility

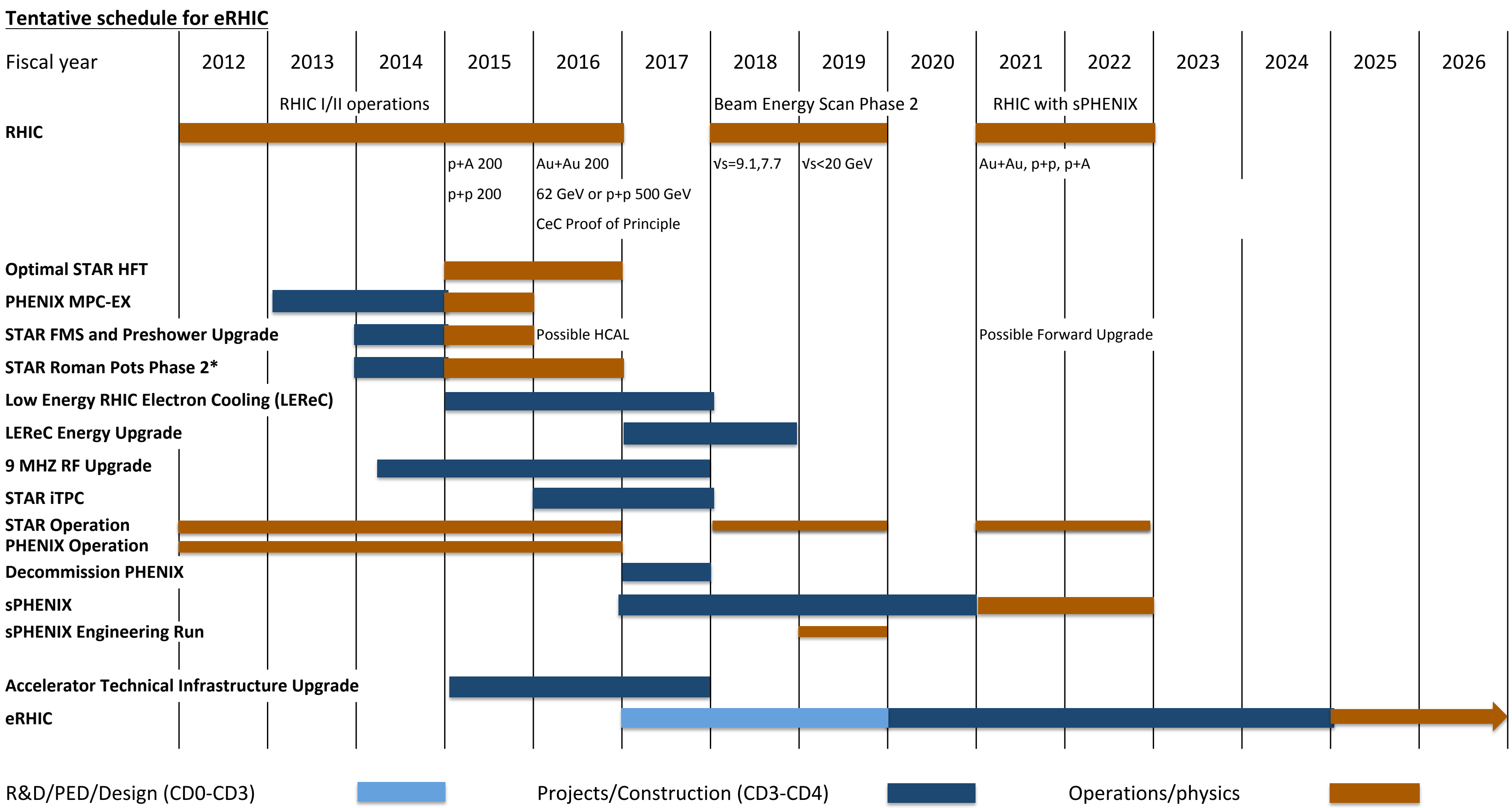
- ERL test facility at BNL.
  E=20 MeV
- Test of high current, high brightness ERL operation
- SC RF gun was tested at 2MV
- The beam from the gun expected by the end of 2014
- Recirculation: 2015/16







eRHIC Schedule



Summary

- The present cost-effective design of ERL-based eRHIC relies on FFAG lattice of recirculation passes and reaches high luminosity ($> 10^{33}$ cm^{-2} s^{-1}) up to 125 GeV CM energy and 145 GeV CM energy for somewhat lower luminosity.
- Studies of design issues specific for the FFAG lattice approach have not revealed showstoppers. Solutions have been found for the optimal FFAG lattice, spreader/combiner, orbit measurement and correction, ion gap formation … .
- R&D is under way on high current polarized electron source (Gatling Gun), strong hadron cooling (Coherent electron Cooling) and high current ERL with key results coming in next two years.

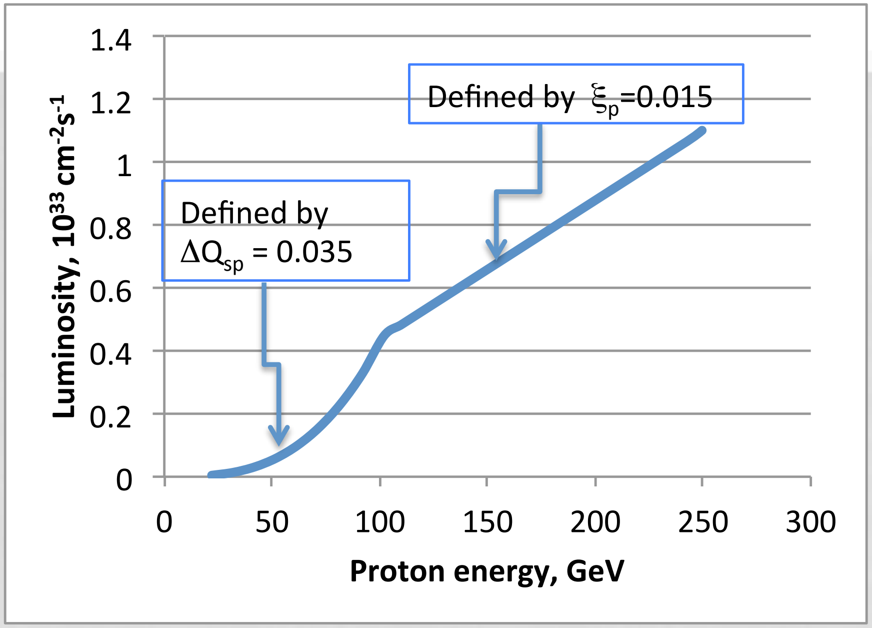
Acknowledgements

for their contributions to the FFAG eRHIC Accelerator design:

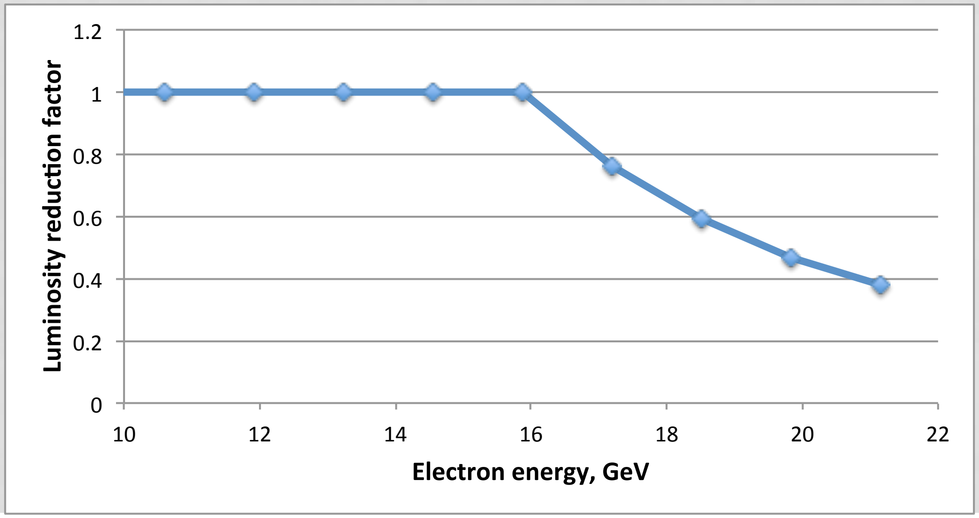
E.C. Aschenauer, S. Belomestnykh, I. Ben-Zvi, S. Berg, M. Blaskiewicz, S. Brooks, C. Brutus, T. Burton, A. Fedotov, D. Gassner, Y. Hao, Y. Jing, D. Kayran, V. N. Litvinenko, C. Liu, G. Mahler, G. McIntyre, W. Meng, F. Meot, T. Miller, M. Minty, B.Parker, I. Pinayev, V.Ptitsyn, T. Roser, J. Skaritka, O. Tchoubar, P. Thieberger, D. Trbojevic, N. Tsoupas, J. Tuozzolo, E. Wang, G. Wang, Q. Wu, W. Xu

Luminosity versus Beam Energy

- Luminosity versus hadron beam energy
  - For 15.9 GeV electron energy or less
  - Limited by hadron beam-beam parameter above 100 GeV and space charge below 100 GeV

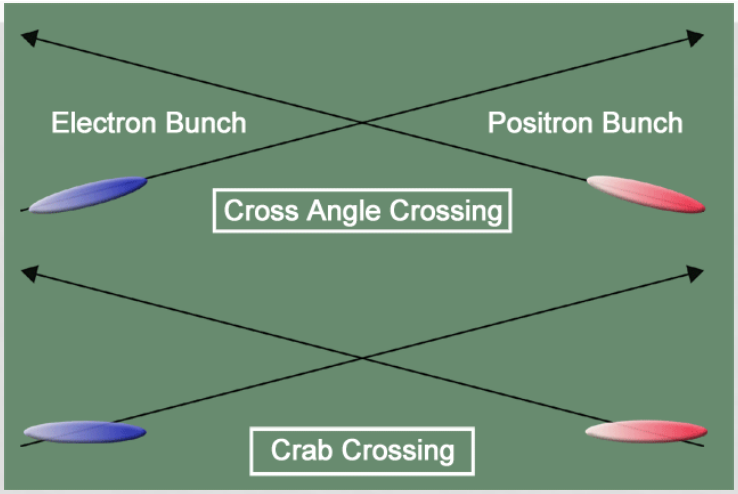


- Luminosity versus electron beam energy
  - Limited by maximum SR power of 12 MW above 15.9 GeV

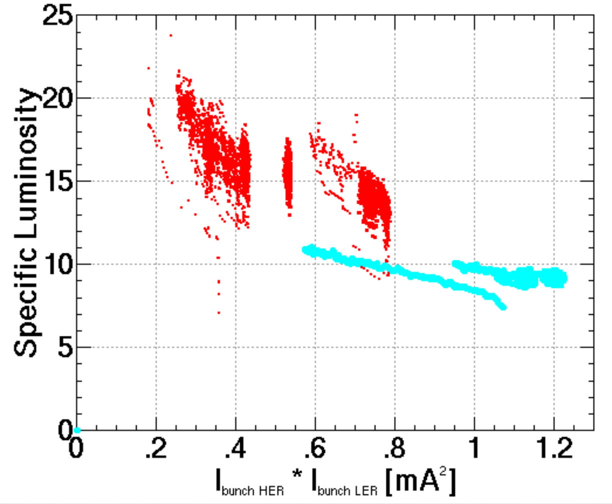


Crab-crossing

Idea Introduced by R. B. Palmer SLAC PUB 4832



Used at KEK B-factory



@ V. Litvinenko, I. Ben-Zvi,
S. Belomestnykh, Q. Wu

✓ Fundamental +3rd + 5th ,

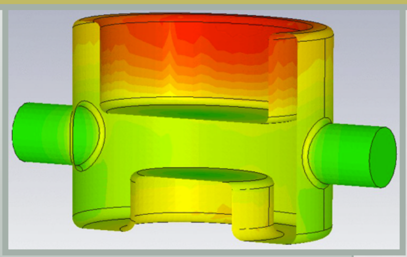
f_{fund}= 183 MHz, V_{fund} = 24 MV, V_{3rd}=1.3 MV, V_{5th} =0.09 MV

OR

Fundamental +2nd + 3rd

f_{fund}= 244 MHz, V_{fund} = 22 MV, V_{2nd}=4.4 MV, V_{3th} =0.5 MV

QWR crab-cavity design (BNL)



✓Crab-cavity design on the basis of the quarter wave SRF cavities has been developed